Abstract

With auxiliary inductive parallel current drive, fluctuation reduction and improved confinement are now routinely achieved in the MST. Most recently, this has resulted in an MST-record electron temperature of 840 eV, a total beta of 14%, and an estimated RFP-record energy confinement time of 9 ms, which substantially exceeds the confinement scaling that has heretofore characterized RFP plasmas. Recent probe measurements show that the current drive induces a reduction in the edge parallel current and an increase in the edge current gradient. The current reduction occurs primarily due to a measured reduction of the MHD dynamo electric field. A similar edge current profile is observed during spontaneously improved confinement, achieved without current drive. The impact on our understanding of the physics of improved confinement will be discussed.

Introduction

-- Old result: auxiliary parallel inductive current drive reduces core-resonant MHD, improves confinement; but improvement limited by new burst-like instability in the edge

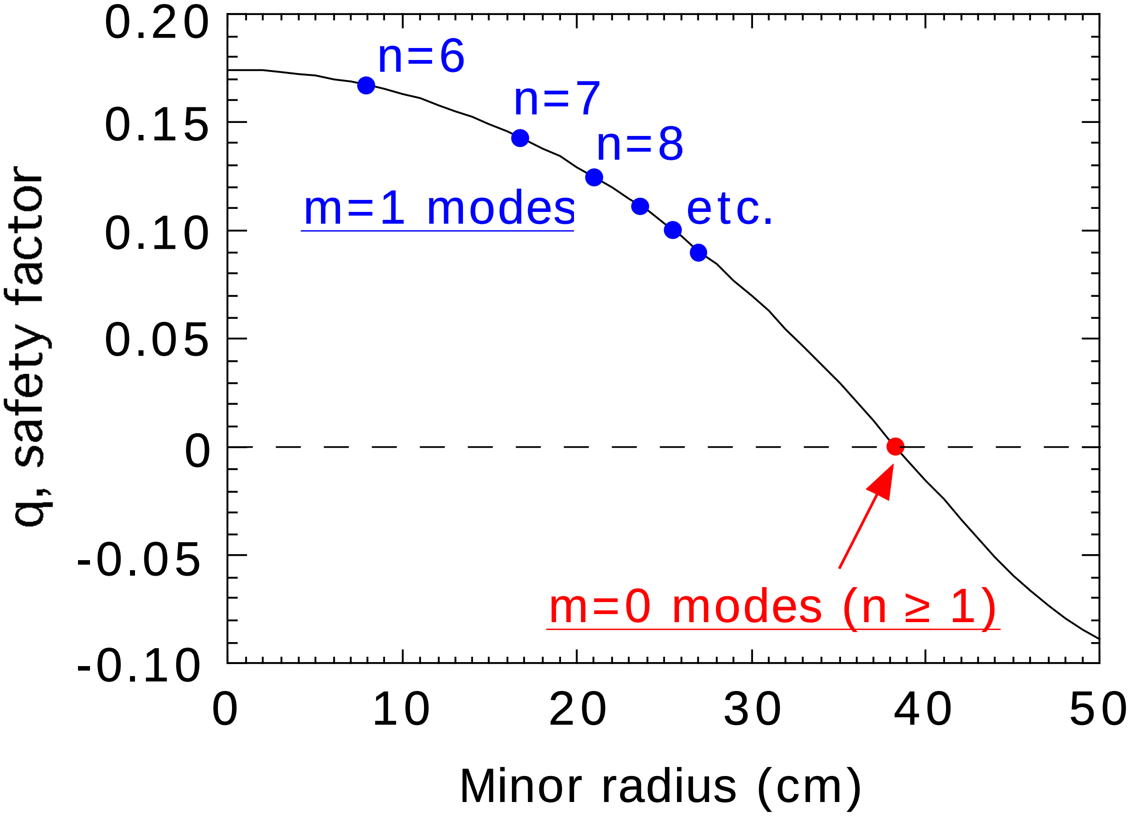
-- New result: improved current drive reduces core instability and suppresses edge bursts, leading to additional confinement improvement

-- New result: observe decrease in edge current, dynamo electric field, and electrical conductivity during improved confinement with current drive

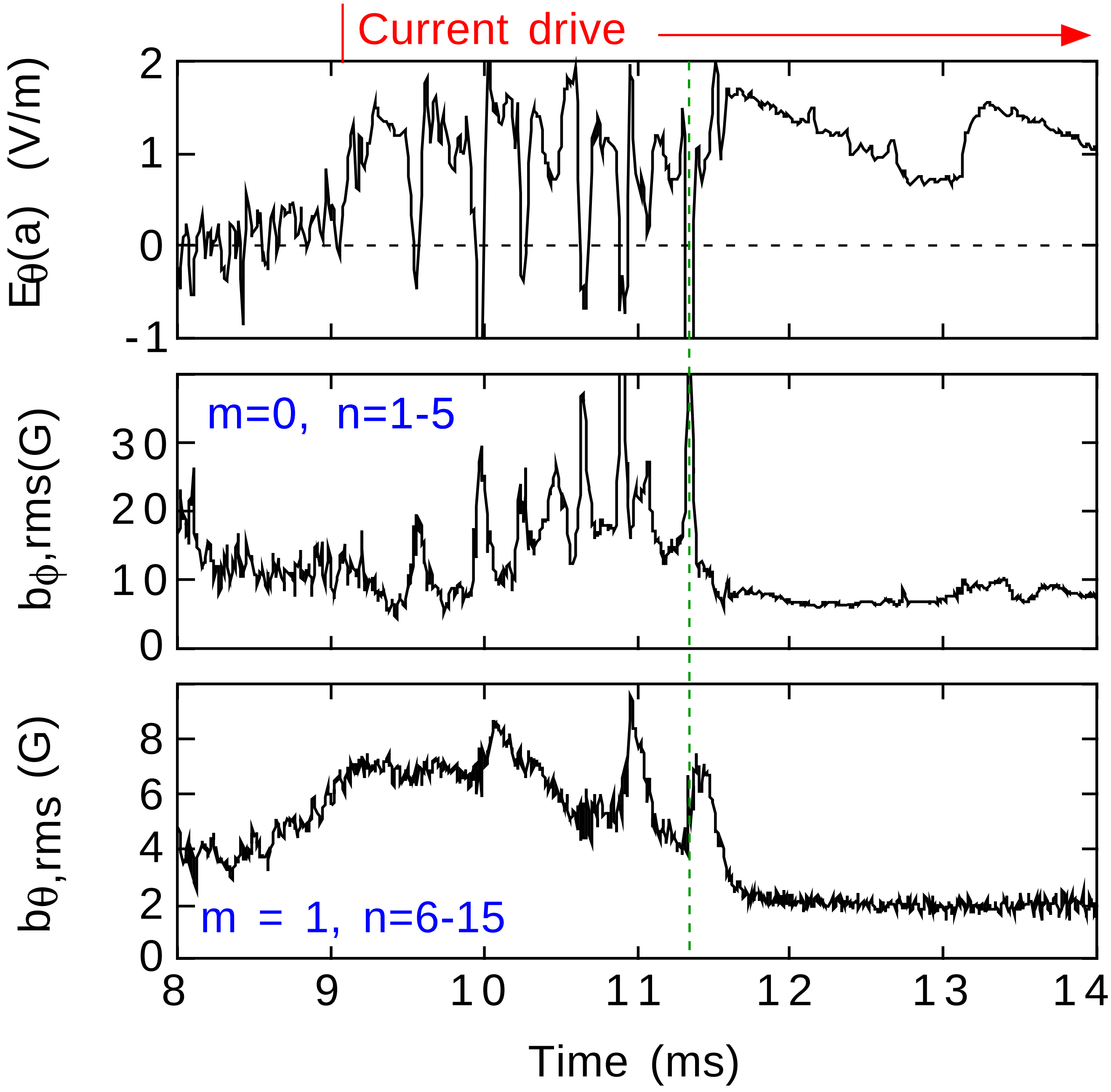
-- New result: similar decrease in edge current and conductivity observed in plasmas with spontaneously improved confinement (without current drive)

The dominant magnetic fluctuations in the MST are m = 0 and m = 1 modes

-- q profile (calculated) typical of discharges with auxiliary current drive:



Bursts of m = 0 instability often occur during auxiliary current drive

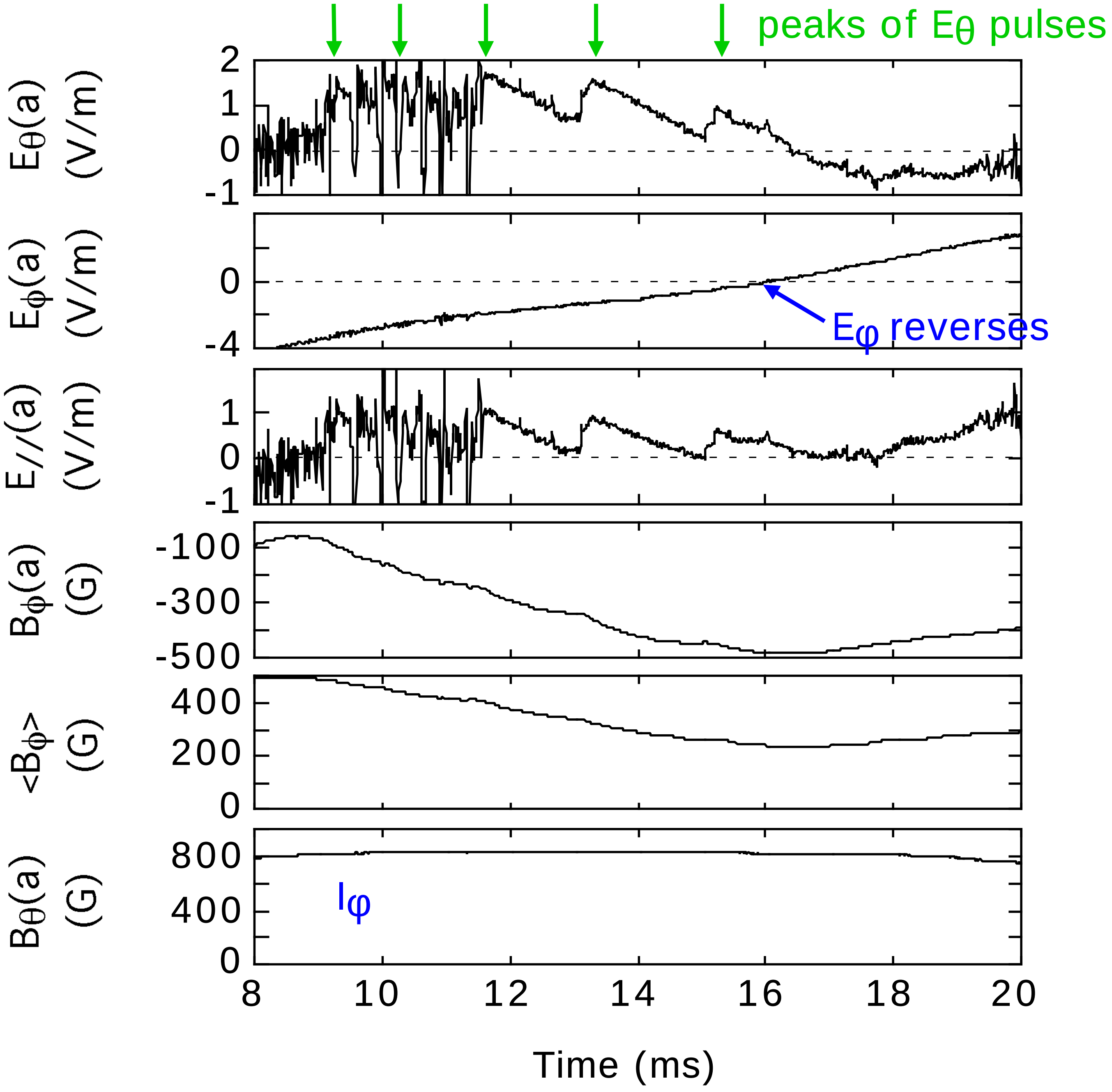


-- Bursts formerly occurred throughout most of current drive phase, impeding confinement improvement, but no longer

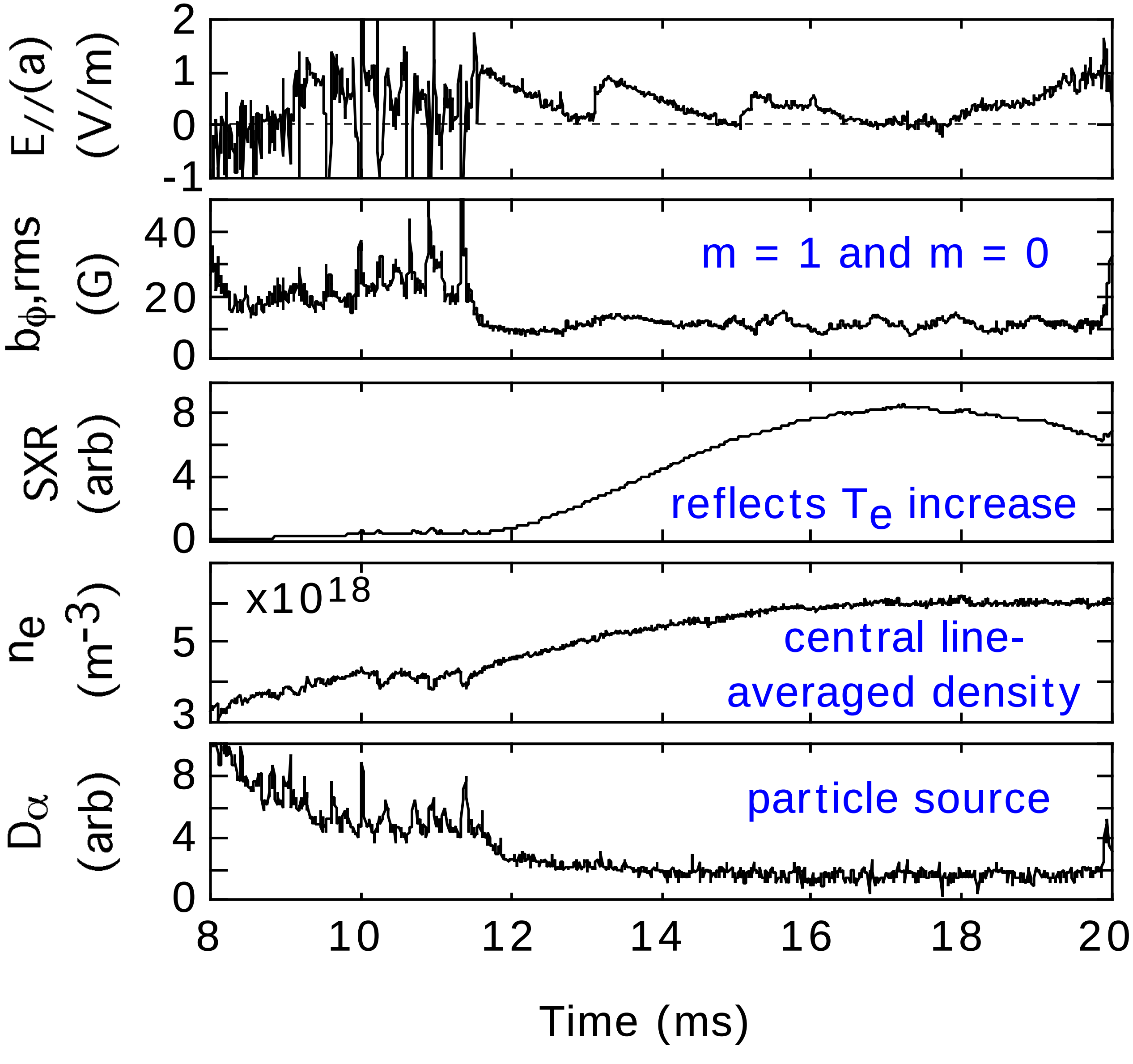
Burst suppression achieved with improved sustainment of surface parallel electric field

-- $E_{//} = \mathbf{E} \cdot \mathbf{B} / B = (E_\theta B_\theta + E_\varphi B_\varphi) / B$

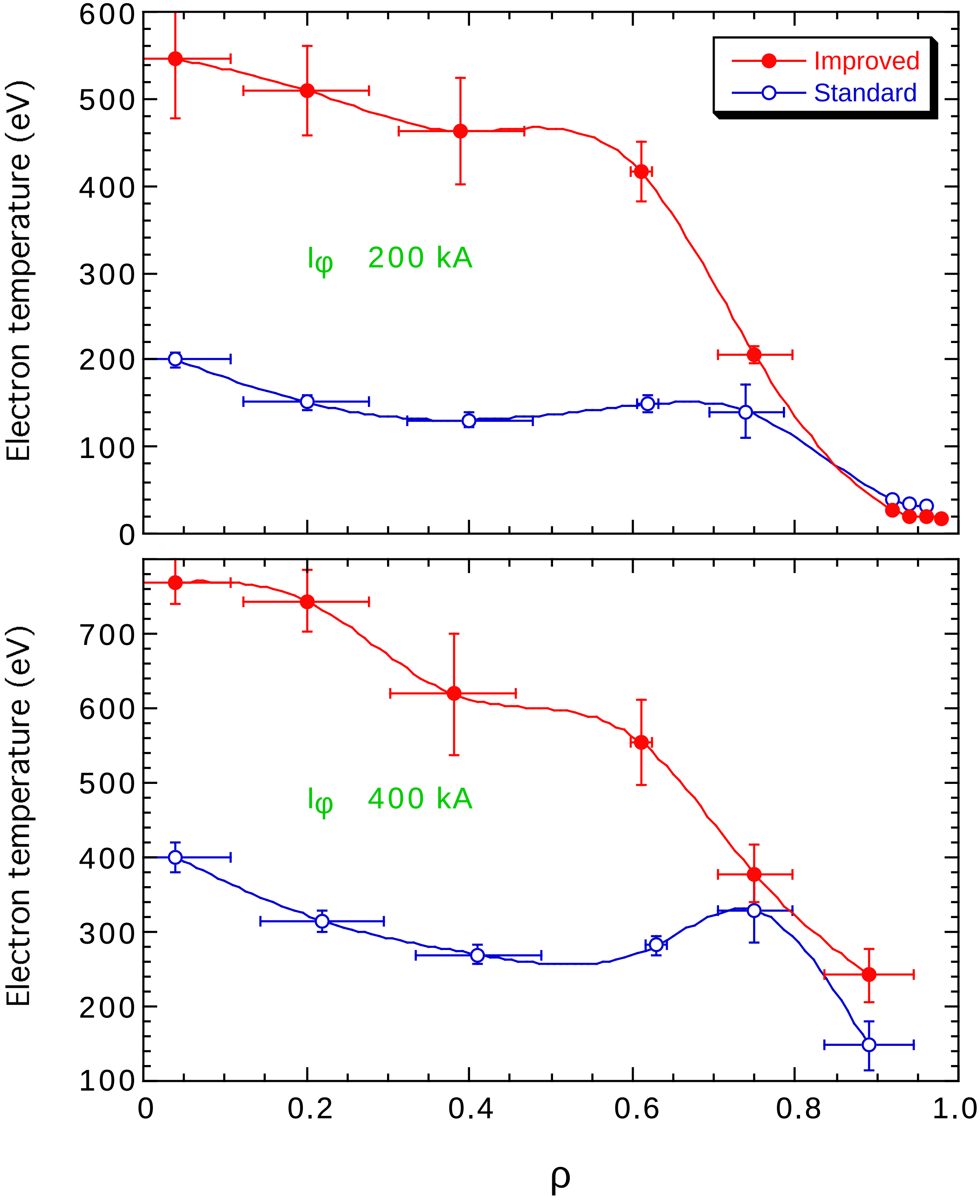
-- Added additional E_θ pulse to original four; space stages in time such that $E_\theta > 0$; added E_φ reversal maintains $E_{//} \geq 0$



With burst suppression, magnetic fluctuations decrease, and the temperature and density increase



Contributing to improved confinement with burst suppression is a substantial increase in the core electron temperature



Beta and confinement increase with burst suppression

	I_φ	$<n_e>$	$T_e(0)$	β_{tot}	β_θ	P_{oh}	dW_{th}/dt	τ_P	τ_E
Standard -->	210	0.8	200	9.0	9.0	2.0	0	0.6	1.4*
Improved -->	210	0.7	546	13.8	16.3	0.9*	0.4	4.7	9.0
Standard -->	430	1.0	400	4.8	4.8	4.0	0	?	1.6*
Improved -->	390	1.0	770	9.2	10.2	2.1*	0.4	?	6.9
Improved -->	470	1.2	840	?	?	?	?	?	?
	(kA)	10^{19} m^{-3}	(eV)	(%)	(%)	(MW)	(MW)	(ms)	(ms)

*Improved ohmic input power estimated via $\int \eta J^2 dV$... see next page

*excluding sawtooth crashes; time-averaged τ_E(standard) 1.0 ms including (regularly occurring) sawtooth crashes; crashes are suppressed during improved confinement

How we estimate improved P_{ohmic}

-- $P_{ohmic} = P_{input} - dW_{magnetic}/dt$ works for standard plasmas

-- P_{input} measured; $dW_{magnetic}/dt$ modeled

-- Models fail with improved confinement, so P_{ohmic} estimated via $\int \eta J^2 dV$, where $\eta \quad Z/T_e^{3/2}/(1 - f_{trapped})$

-- estimated Z_{eff} (related to Z)   1.7 @ 210 kA and 2.0 @ 390 kA

-- $f_{trapped}(r)$ and $J(r)$ calculated with toroidal equilibrium model constrained by measurements of, e.g, edge profiles of J and B

Has MST reached its β limit?

-- Doubtful.

-- Observe no onset of internal MHD, wall modes...

-- Instead, β believed limited by:

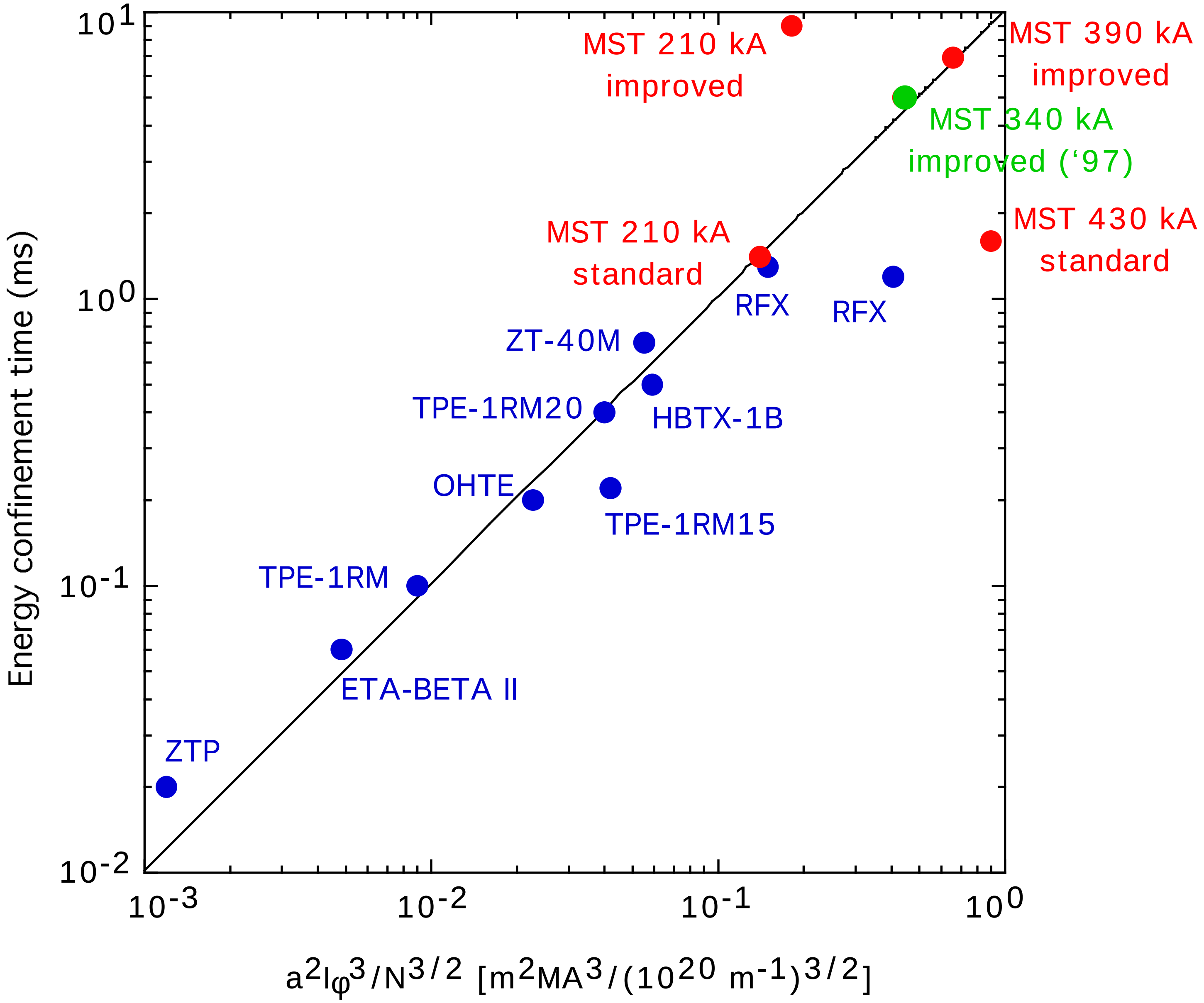
(1) finite duration of improved confinement coupled with

(2) finite, reduced Pohmic

-- Presently working to lengthen periods of improved confinement and apply auxiliary heating

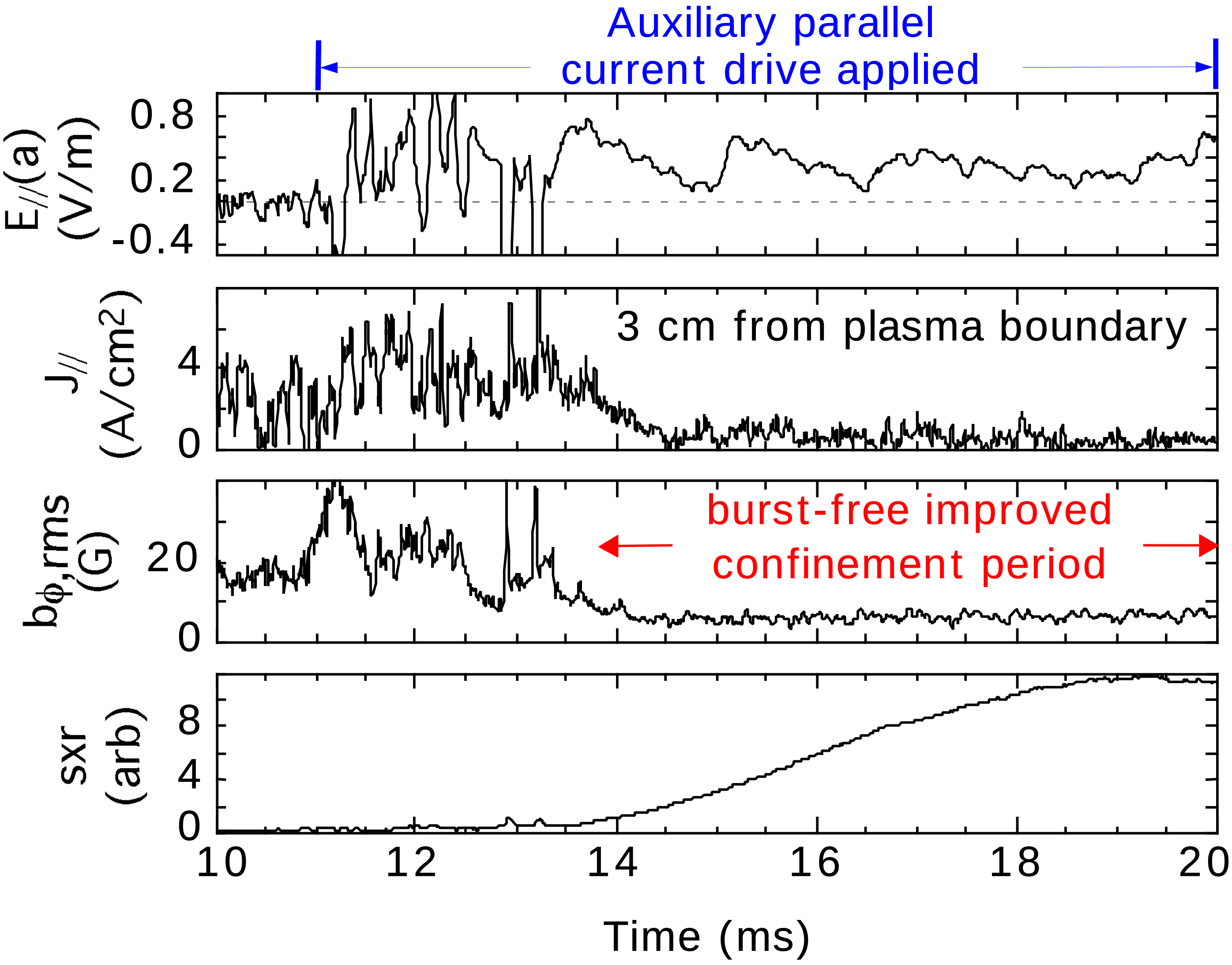
-- Ideal MHD β limit   50%

At 210 kA, estimated τ_E with burst suppression substantially exceeds RFP "constant β" scaling for the first time



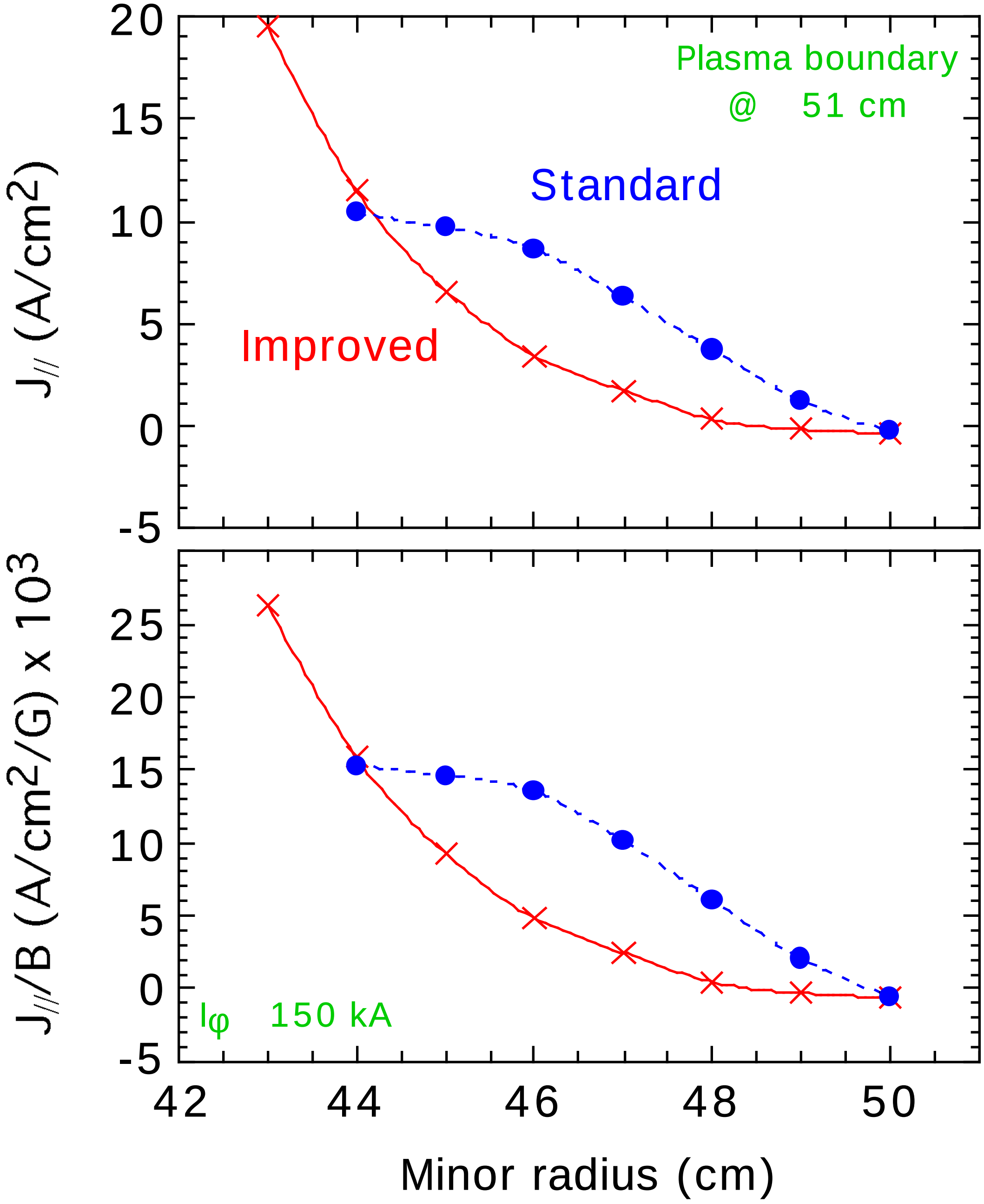
Goal of auxiliary current drive is to shape J(r) to reduce current-driven m = 1 magnetic fluctuations   Is this what is happening in these plasmas? J(r) measurements have just begun…

Edge current is reduced with auxiliary current drive and burst suppression*



*Phys. Plasmas **7**, 3491 (2000) ask for reprint

With burst suppression, edge current is reduced and edge current profile steepens



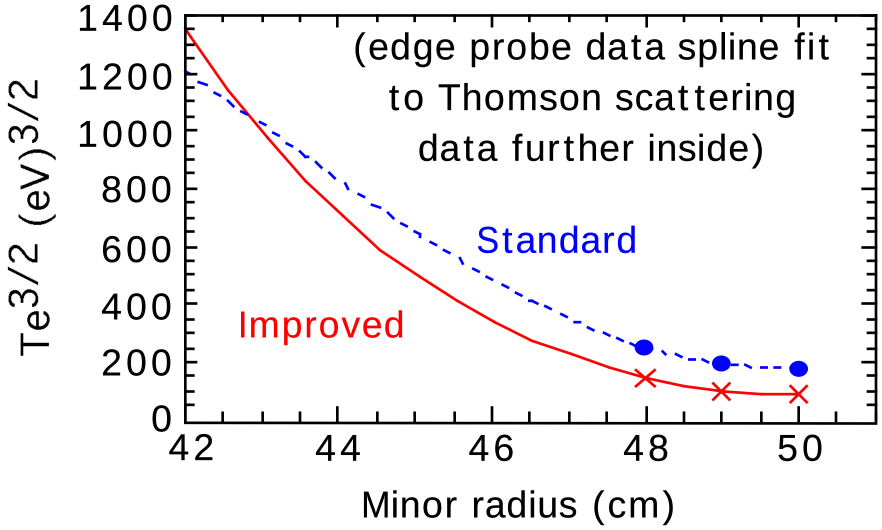
With burst suppression, edge dynamo emf and(?) electrical conductivity drop

-- Parallel Ohm's law: $J = \sigma(E_{applied} + E_{dynamo})$

-- $E_{dynamo} = \langle v \times b \rangle$, measured with magnetic and spectroscopic probes 3 cm from plasma boundary:

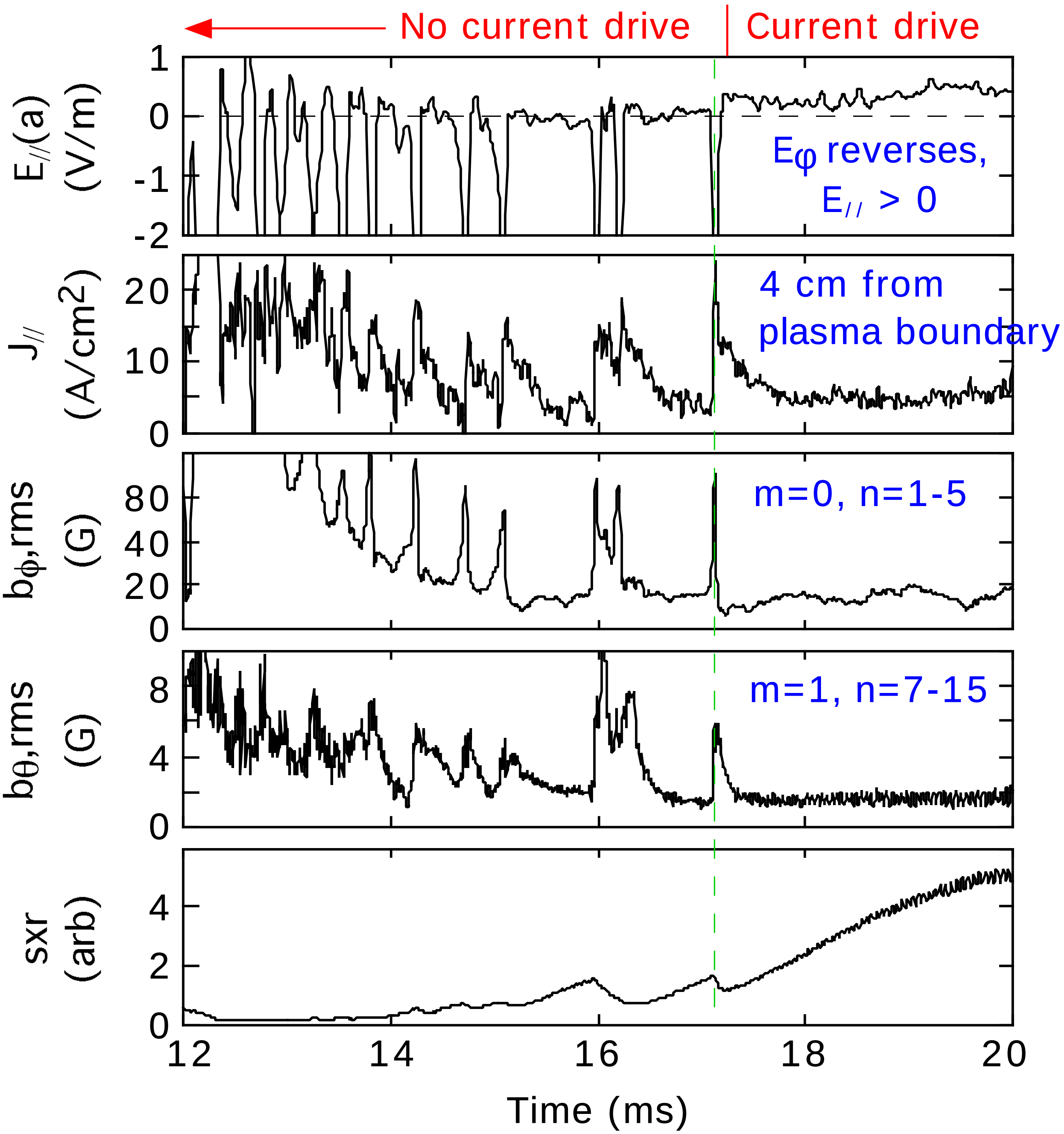
E_{dynamo} (standard during sawtooth crashes) = 9.2 V/m
E_{dynamo} (standard between crashes) = 0.83 V/m
E_{dynamo} (improved with burst suppression) = 0.16 V/m

-- σ $T_e^{3/2}$ may also decrease (but ΔZ unknown):



-- Thus, E_{dynamo} and/or σ decrease more than $E_{applied}$ increases

Edge current also reduced between bursts in spontaneous improved confinement (without auxiliary current drive)


No current drive | Current drive

E_φ reverses, $E_{//} > 0$

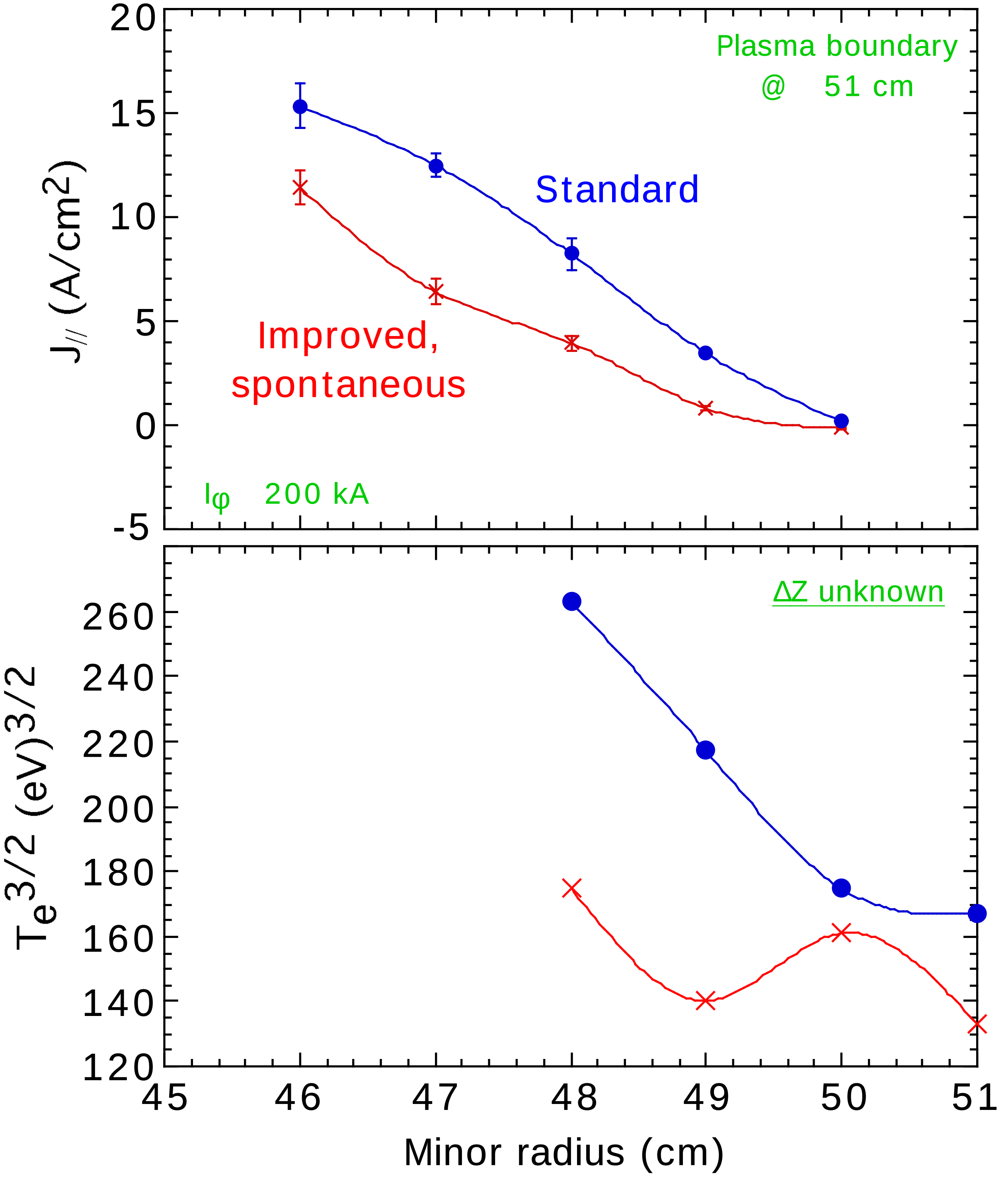
4 cm from plasma boundary

m=0, n=1-5

m=1, n=7-15

-- $J_{//}$(standard) between crashes (4 cm from plasma boundary)   12.5 A/cm^2

Edge J and σ(?) reduced between bursts in spontaneous improved confinement



-- E_{dynamo} not yet measured, but magnetic fluctuations drop... E_{dynamo} does too?

What do these edge current measurements imply, if anything?

-- Some MHD simulations (by Carl Sovinec) of RFP plasmas with stable current profile exhibited reduction of edge current (due to drop in edge dynamo) similar to those shown above

-- Do the edge current profiles in the two cases shown above reflect an overall more stable current profile? Magnetic fluctuations drop in both cases, so is certainly possible

-- Then how is a stable current profile achieved spontaneously?

-- Besides bursts, edge current reduction, etc., these two types of plasma share other similarities...

-- For example, spontaneous improved confinement depends on sufficiently large (reversed) $B_\varphi(a)$ [$dB_\varphi(a)/dt = 0$]

-- Large $B_\varphi(a)$ intrinsic to inductive auxiliary current drive

-- Only clear (known) difference between these plasmas is the burst repetition rate (bursts occur regularly without auxiliary current drive)

-- One hypothesis: the physics underlying the improved confinement in these plasmas is fundamentally the same (under investigation)

-- Would imply that the reduction of magnetic fluctuations with current drive results from something other than the current drive

Summary

-- With improved current drive, core and edge fluctuations reduced, confinement/beta improved

-- No obvious beta limit reached

-- At low current, exceed historical RFP confinement scaling

-- Reduction of edge current observed during improved confinement with and without auxiliary current drive

-- Much of the physics underlying the improved confinement is as yet unknown